Chemical Research in Toxicology

Rapid Report

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"Juice Monsters": Sub-Ohm Vaping and Toxic Volatile Aldehyde Emissions

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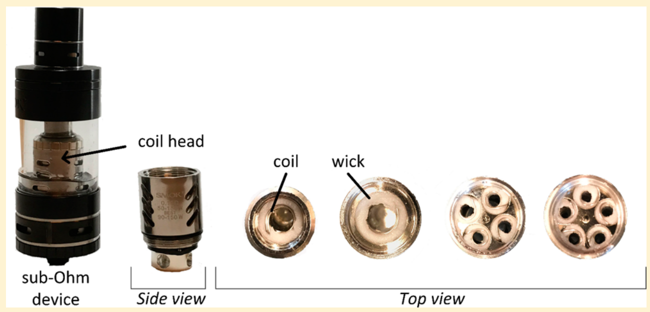
Supporting Information

ABSTRACT: An emerging category of electronic cigarettes (ECIGs) is sub-Ohm devices (SODs) that operate at ten or more times the power of conventional ECIGs. Because carcinogenic volatile aldehyde (VA) emissions increase sharply with power, SODs may expose users to greater VAs. In this study, we compared VA emissions from several SODs and found that across device, VAs and power were uncorrelated unless power was normalized by coil surface area. VA emissions and liquid consumed were correlated highly. Analyzed in light of EU regulations limiting ECIG liquid nicotine concentration, these findings suggest potential regulatory levers and pitfalls for protecting public health.



Electronic cigarettes (ECIGs) are battery-operated devices that deliver nicotine to users via an inhalable aerosol mist.[1−5] They have an electrical heating coil that physically contacts a liquid-saturated wick. When activated by the user, the coil heats and vaporizes the nicotine-containing liquid, which is composed primarily of propylene glycol (PG) and vegetable glycerin (VG). Available in hundreds of flavors,[6] and particularly appealing to youth,[7] this increasingly popular and diverse class of tobacco products[8] has undergone continuous, major design developments ever since its introduction to the US market in 2007. The most recent models include a category commonly known as "sub-Ohm". The term refers to devices with heating coils whose electrical resistance (R) is well below 1 Ohm. Because power (P) is inversely proportional to resistance ($P = V^2/R$, where V = volts), these devices can operate at high power (50−300 W) with extant battery technology, whereas conventional ECIGs (R = 1.8−3.3 Ohm) typically operate at powers less than 10 W.[9] On social media, sub-Ohm devices (SODs) are described as producing larger exhaled clouds, warmer inhaled aerosols, and more flavor.[10] Because they consume large quantities of liquid, a concern to price-conscious users, they are sometimes referred to as "juice monsters." Until recently, SODs have been the purview of ECIG aficionados who built their own units. Today, ready-made sub-Ohm ECIGs are widely available for purchase, making them accessible to a broader segment of the population.

One public health concern raised by the growing availability of SODs is the possibility that they may expose users to higher levels of volatile aldehydes (VAs), a class of harmful compounds that are well-known thermal degradation products of PG and VG. VAs are thought to be major causative agents in lung disease among cigarette smokers.[11] With conventional ECIG devices, VA emissions, including the carcinogen formaldehyde, have been shown to increase considerably as power increases,[9,12−16] likely due to the higher temperatures attained at higher power.[14] Extrapolating the data from conventional devices would suggest that in a few puffs SODs expose users to VA emissions equivalent to tens to hundreds of cigarettes. Potentially mitigating this dire picture is the fact that SODs typically distribute their high power over multiple heating coils operating in parallel in a single "coil head", while conventional devices typically use only one coil (see Figure S1 in Supporting Information). This parallelization, and the larger physical dimensions of sub-Ohm coils and wicks, may result in lower operating temperatures than if a conventional single-coil ECIG device were operated at the same power and therefore may mitigate VA emissions. Indeed, when measuring VAs in the aerosol generated from single and dual-coil ECIGs, the single-coil ECIG generated significantly higher VAs relative to the dual-coil ECIG.[13]

To date, there are no published data addressing VA emissions from SODs. In this two-arm study, we measured VA yields (a) from four popular SOD coil head models (TF-Q4, V8-Q4, V8-T8, and V8-T10; SMOK TFV series) at a constant power of 50 W and (b) for varying power (50, 75, 100 W) using the V8-T8 coil head. Samples of each coil head model were disassembled, and the total coil surface area was calculated based on the coil wire diameter (measured by caliper), length of coil wire, and number of coils (one up to ten coils,

Received: July 28, 2017
Published: September 22, 2017

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DOI: 10.1021/acs.chemrestox.7b00212
Chem. Res. Toxicol. 2017, 30, 1791−1793

depending on model). A variable wattage Joyetech cuboid mod battery was used to power the devices. For comparison, we also measured VA yields from a conventional Vapor Fi Platinum (VF) ECIG at two power levels (4, 11 W). Aerosols were generated using a digital vaping machine and sampled for VA species using DNPH-coated silica cartridges. Samples were analyzed by high performance liquid chromatography. Detailed procedures are provided in the Supporting Information.

A summary of findings is presented in Table S1 and Figures 1 and 2. Consistent with previous studies, we found that within device, power predicted aldehyde emissions (SOD, R^2 = 0.93, p < 0.0001; VF, R^2 = 0.40, p < 0.01) and liquid consumed (SOD, R^2 = 0.98, p < 0.0001; VF, R^2 = 0.89, p < 0.0001). However, device type modified the relationship between power and aldehyde emissions. After pooling data across devices, power was unrelated to emissions (R^2 = 0.01). As shown in Figure 1a, the SOD and VF devices appeared to fall on different lines, and SOD emissions were far lower than what would have been predicted by extrapolating VF emissions to the higher powers of the SODs. Relative to SODs, the conventional ECIG showed much greater variability in VA yields.

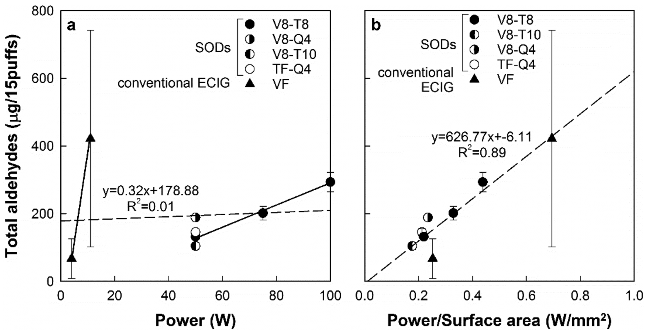

Figure 1. (a) Total VA yield versus power. Solid lines show that, within a device, increasing power results in an increase in emissions. Dashed line represents the best fit across all conditions (R^2 = 0.01, p > 0.4). (b) Total VA yield versus power per coil surface area. Dashed line represents best fit across all conditions (R^2 = 0.89, p < 0.001). Error bars: SD.

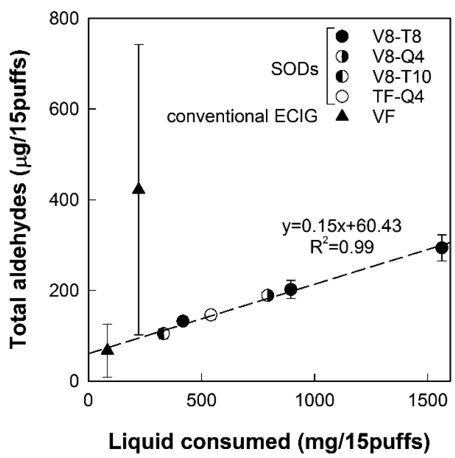

Figure 2. Liquid consumed highly predicts aldehyde emissions (R^2 = 0.99, p < 0.0001). The VF condition at 11 W (second data point from the left) exhibited far greater aldehyde yields per unit liquid consumed than the other conditions. Figure S2 shows that for this condition, it is highly probable that the coil was running dry causing an increase in VA production. Error bars: SD.

Because ECIG VA emissions are known to increase with temperature,[14,17] a useful approach is to view the interaction between power and device geometry on VA emissions through principles of heat transfer, which relate geometry, power, and temperature. In broad terms, the rate at which heat is dissipated (Q, Watts) from a hot surface (e.g., the surface of the heating coil) is proportional to the product of its area A (m^2) and its temperature relative to its cooler surroundings, ΔT (°C): $Q \propto A\Delta T$. When the coil is powered, its temperature rises until the rate of electrical power input W (Watts) is balanced by the rate heat dissipates from the surface: $W = Q$. By combining these two equations, it can be shown that the maximum temperature rise is proportional to the electrical power input per unit area: $\Delta T \propto W/A$. Figure 1b shows the aldehyde yields plotted against power per unit area and reveals that the VA and power per unit area are far better correlated across device than VA and power (R^2 = 0.89 vs 0.01). Furthermore, at constant power (50 W), we found that an increase in coil surface area resulted in a decrease in VA emissions (R^2 = 0.76, p < 0.05) and mass of liquid consumed (R^2 = 0.63, p < 0.05). Clearly, for our data set, power per unit area is a superior predictor of VA yield, and, likely, other thermally driven toxicant emissions. While the physics suggest it will, determining whether this finding holds generally will require future work with a wider range of products and operating conditions.

Interestingly, excluding the 11W VF condition, we found that total VA emissions (as well as nearly all individual aldehyde species, including the carcinogen formaldehyde) were correlated strongly with liquid consumed (Figure 2). Because liquid consumed is directly proportional to nicotine yield for a given liquid,[20] this finding may be particularly relevant to potential regulatory strategies aimed at limiting nicotine delivery to ECIG users. For example, if liquid nicotine concentration were limited by a regulatory action (as did the EU in 2014),[21] users could maintain a given nicotine intake per puff or per second[22] by increasing device power. As a result, liquid consumption and therefore nicotine yield would increase. Under such a scenario, users' nicotine intake could remain constant, while aldehyde exposure would increase. Such an outcome is plausible and highlights the need to consider multiple factors simultaneously when designing regulations. We caution that while Figure 2 is intuitively appealing, the relative proportions of individual aldehyde species vary somewhat across conditions. Because the relative hazard of various aldehyde mixtures of a given total concentration is not well characterized, the degree to which total aldehydes plotted in Figure 2 scale with hazard is unknown.

In summary, we found that counter to expectations, high power devices do not necessarily produce high VA (or formaldehyde) emissions. The relationship between power and VA yields is evidently mediated by device design. A parameter that plausibly captures this dependence is power per unit heating coil surface area. We also found that across designs, liquid consumption predicts VA yields. Limitations of this study include the small number of devices tested. Additionally, only gas-phase aldehydes were analyzed; there may be significant quantities of VAs present in the particle phase of the ECIG aerosol,[18,19] though it is unlikely that analysis of particle phase aldehyde species would have changed the basic observations of this study.

DOI: 10.1021/acs.chemrestox.7b00212
Chem. Res. Toxicol. 2017, 30, 1791−1793

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/acs.chemrestox.7b00212.

Experimental procedure, table, figures (PDF)

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The manuscript was written through contributions of all authors.

Funding

This work was supported by the National Institute on Drug Abuse of the National Institutes of Health (Grant No. P50DA036105) and the Center for Tobacco Products of the U.S. Food and Drug Administration. The content is solely the responsibility of the authors and does not necessarily represent the official views of the National Institutes of Health or the Food and Drug Administration.

Notes

The authors declare the following competing financial interest(s): Dr. Eissenberg and Dr. Shihadeh are paid consultants in litigation against the tobacco industry and are both named on a patent application for a device that measures the puffing behavior of electronic cigarette users.

■ ABBREVIATIONS

ECIG, electronic cigarette; *P*, power; PG, propylene glycol; *R*, resistance; *A*, surface area; SOD, sub-Ohm device; *V*, volts; VAs, volatile aldehydes; VG, vegetable glycerin

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DOI: 10.1021/acs.chemrestox.7b00212
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